

Predictions for $B \rightarrow \tau \bar{\mu} + \mu \bar{\tau}$

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The observation of $B \rightarrow \tau \bar{\mu} + \mu \bar{\tau}$ at present experiments would be a clear sign of new physics. In this paper we calculate this process in a 2HDM framework where the decay is mediated by the exchange of spin zero particle with flavour changing neutral current couplings. If we identify the scalar with the the newly discovered state at LHC with a mass ~ 125 GeV then we get $BR(B_s \rightarrow \tau \bar{\mu} + \mu \bar{\tau}) \sim 10^{-6}$ and $BR(B_d \rightarrow \tau \bar{\mu} + \mu \bar{\tau}) \sim 10^{-7}$. We also calculate this process in minimal supersymmetric standard model and find $BR(B_s \rightarrow \tau \bar{\mu} + \mu \bar{\tau}) \sim 10^{-11}$.

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I. INTRODUCTION

Flavor changing neutral current (FCNC) events are rare in the Standard Model (SM) both in the quark and the lepton sectors. These processes can be affected by new physics (NP). FCNC involving the third family quark and leptons are interesting as their larger masses make them more susceptible to new physics effects in various extensions of the SM. As an example, in certain versions of the two Higgs doublet models (2HDM) the couplings of the new Higgs bosons are proportional to the masses and so new physics effects are more pronounced for the heavier generations. Moreover, the constraints on new physics involving, specially the third generation leptons and quarks, are somewhat weaker allowing for larger new physics effects. Hence, in the down quark sector there is intense interest in the search for NP in FCNC $b \rightarrow s$ and $b \rightarrow d$ transitions in $B_{d,s}$ mixing, $b \rightarrow s(d)q\bar{q}$ and $b \rightarrow s(d)\ell^+\ell^-$ decays. Many measurements in the B sector have constrained NP effects though slight discrepancies from SM predictions still remain in several decays [1]. In the up quark sector one can look for NP in the processes $t \rightarrow c(u)$ transitions [2].

In the lepton sector FCNC decays are severely suppressed and lepton number for each family is conserved in the SM. Therefore, FCNC effects and lepton flavor violation in this sector are sensitive probes of NP. The presence of neutrino masses and mixing suggest NP in the lepton sector which in turn could enhance FCNC effects and lepton flavor violation. It is interesting that measurements involving the tau lepton show some discrepancies from SM expectations. The branching ratio of $B \rightarrow \tau\nu_\tau$ shows some tension with the SM predictions [3] though more recent measurement are consistent with the SM [4]. This could indicate NP [5], possibly coming from an extended scalar or gauge sector. There is also a seeming violation of universality in the tau lepton coupling to the W suggested by the LEP II data which could indicate new physics associated with the third generation lepton [6].

More recently, the BaBar collaboration with their full data sample of an integrated luminosity 426 fb^{-1} has reported the measurements of the quantities [7]

$$\begin{aligned} R(D) &= \frac{BR(\bar{B} \rightarrow D\tau^-\bar{\nu}_\tau)}{BR(\bar{B} \rightarrow D\ell^-\bar{\nu}_\ell)} = 0.440 \pm 0.058 \pm 0.042, \\ R(D^*) &= \frac{BR(\bar{B} \rightarrow D^*\tau^-\bar{\nu}_\tau)}{BR(\bar{B} \rightarrow D^*\ell^-\bar{\nu}_\ell)} = 0.332 \pm 0.024 \pm 0.018. \end{aligned} \quad (1)$$

The SM predictions for $R(D)$ and $R(D^*)$ are [7–9]

$$\begin{aligned} R(D) &= 0.297 \pm 0.017, \\ R(D^*) &= 0.252 \pm 0.003, \end{aligned} \quad (2)$$

which deviate from the BaBar measurements by 2σ and 2.7σ respectively. The BaBar collaboration themselves reported a 3.4σ deviation from SM when the two measurements of Eq. 1 are taken together. This result, if confirmed, could indicate NP involving new charged scalar or vector boson states [10]. Models with new charged scalars or charged vector bosons also include neutral particles that can cause FCNC effects.

In this paper we will focus on the process $B_{s,d} \rightarrow \ell_i\ell_j$. This involves two FCNC interactions- one in the quark and one in the lepton sector. Typically one believes that this process will be very small even with new physics and in many NP models this is indeed true. This is because in these NP models this FCNC process arises in loops and is suppressed. In this paper we will focus on the decay $B \rightarrow \tau\bar{\mu} + \mu\bar{\tau}$ and make predictions for its rate. This decay was considered in earlier papers in various extensions of the SM [11]. In this work we will calculate the process in two scenarios representing two extension of the SM.

In the first scenario we will consider this process mediated by a scalar which we will call X in a two higgs doublet framework (2HDM). We will identify X with the newly discovered particle, with mass $\sim 125 \text{ GeV}$, observed at LHC [12, 13] with supporting evidence for its existence from Fermilab [14]. In this case $B \rightarrow \tau\bar{\mu} + \mu\bar{\tau}$ is generated at tree level due to the presence of bqX and $\tau\mu X$ couplings. The coupling bqX can be constrained by $B_{d,s}$ mixing while the $\tau\mu X$ couplings can be constrained from rare τ decays. Recently in Ref. [15, 16] these

coupling were considered and it was noticed that the $\tau\mu X$ coupling could be of similar size as the SM higgs to $\tau\tau$ coupling. Since $B_{s,d}$ are pseudoscalars then clearly X must be a pseudoscalar or have both parity conserving and parity violating couplings to quarks and leptons. The spin parity of the X particle is not yet known though various strategies that allow for the spin and parity determination are being actively pursued [17]. In this scenario the branching ratio for $B \rightarrow \tau\bar{\mu} + \mu\bar{\tau}$ can be significant and can potentially be observed at LHCb. In the second scenarios we will consider a popular extension of the SM- the minimal supersymmetric SM (MSSM). Here the FCNC couplings arise via loops and so our expectation is that the branching ratio for $B \rightarrow \tau\bar{\mu} + \mu\bar{\tau}$ will be tiny. The main point here is that if this process were to be observed at the LHCb in the near future this would indicate the presence of a rather non-traditional NP with appreciable tree level FCNC couplings in the lepton sector and a light spin zero mediator.

The paper is organized in the following manner. In the next section we describe the general effective Hamiltonian for $b \rightarrow sl_i^- l_j^+$ decays. In the following section we consider the decay $B \rightarrow \tau\bar{\mu} + \mu\bar{\tau}$ in a 2HDM framework with FCNC higgs couplings. This is followed by a calculation of $B \rightarrow \tau\bar{\mu} + \mu\bar{\tau}$ in MSSM. Finally we summarize our results and present our conclusions.

II. EFFECTIVE HAMILTONIAN

In this section we discuss the effective Hamiltonian for $b \rightarrow q(=d,s)l_i^- l_j^+$ transitions. We will focus on the $b \rightarrow sl_i^- l_j^+$ Hamiltonian as the $b \rightarrow dl_i^- l_j^+$ Hamiltonian can be obtained from it with the obvious replacements.

The effective Hamiltonian for the quark-level transition $b \rightarrow sl_i^- l_j^+$ ($l = e, \mu, \tau$) in the SM is given by

$$\begin{aligned} \mathcal{H}_{\text{eff}}^{SM} = & -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left\{ \sum_{i=1}^6 C_i(\mu) \mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} [\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R)b] F^{\mu\nu} \right. \\ & \left. + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma^\mu P_L b) L_{ij}^\mu + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma^\mu P_L b) L_{ij}^{5\mu} \right\}, \end{aligned} \quad (3)$$

where $L_{ij}^\mu = \bar{l}_i \gamma^\mu l_j$, $L_{ij}^{5\mu} = \bar{l}_i \gamma^\mu \gamma_5 l_j$, and $P_{L,R} = (1 \mp \gamma_5)/2$. The operators \mathcal{O}_i ($i = 1, \dots, 6$) correspond to the P_i in [18], and $m_b = m_b(\mu)$ is the running b -quark mass in the $\overline{\text{MS}}$ scheme. We use the SM Wilson coefficients as given in [19].

The total effective Hamiltonian for $b \rightarrow sl_i^- l_j^+$ in the presence of new physics operators with all the possible Lorentz structure excluding tensor once can be expressed as [20]

$$\mathcal{H}_{\text{eff}}(b \rightarrow sl_i^- l_j^+) = \mathcal{H}_{\text{eff}}^{SM} + \mathcal{H}_{\text{eff}}^{VA} + \mathcal{H}_{\text{eff}}^{SP}, \quad (4)$$

where $\mathcal{H}_{\text{eff}}^{SM}$ is given by Eq. (3), and the NP contributions are

$$\mathcal{H}_{\text{eff}}^{VA} = -N_F \left\{ R_V (\bar{s}\gamma^\mu P_L b) L_{ij}^\mu + R_A (\bar{s}\gamma^\mu P_L b) L_{ij}^{5\mu} + R'_V (\bar{s}\gamma^\mu P_R b) L_{ij}^\mu + R'_A (\bar{s}\gamma^\mu P_R b) L_{ij}^{5\mu} \right\}, \quad (5)$$

$$\mathcal{H}_{\text{eff}}^{SP} = -N_F \left\{ R_S (\bar{s} P_R b) L_{ij} + R_P (\bar{s} P_R b) L_{ij}^5 + R'_S (\bar{s} P_L b) L_{ij} + R'_P (\bar{s} P_L b) L_{ij}^5 \right\}, \quad (6)$$

where $N_F = \frac{4G_F}{\sqrt{2}} \frac{\alpha_{em}}{4\pi} V_{ts}^* V_{tb}$, $L_{ij} = \bar{l}_i l_j$, and $L_{ij}^5 = \bar{l}_i \gamma_5 l_j$. In the above expressions, R_i, R'_i ($i = V, A, S, P$) are the NP effective couplings which are in general complex.

In terms of all the Wilson coefficients, the branching ratio for the decay $B_s \rightarrow l_i^- l_j^+$ can be obtained from

$$\begin{aligned} Br(B_s \rightarrow l_i^- l_j^+) = & \frac{\tau_{B_s}}{\hbar} \frac{f_{B_s}^2 G_F^2 m_{B_s} \alpha_{em}^2 |V_{tb} V_{ts}^*|^2}{64\pi^3} \sqrt{\left[1 - \left(\frac{m_i + m_j}{m_{B_s}}\right)^2\right] \left[1 - \left(\frac{m_i - m_j}{m_{B_s}}\right)^2\right]} \\ & \left\{ \left[1 - \left(\frac{m_i + m_j}{m_{B_s}}\right)^2\right] |F_V(m_i - m_j) + F_S|^2 + \left[1 - \left(\frac{m_i - m_j}{m_{B_s}}\right)^2\right] |F_A(m_i + m_j) + F_P|^2 \right\}, \end{aligned} \quad (7)$$

where

$$\begin{aligned}
F_V &= C_9 + R_V - R'_V, \\
F_A &= C_{10} + R_A - R'_A, \\
F_S &= r_\chi(R_S - R'_S), \\
F_P &= r_\chi(R_P - R'_P),
\end{aligned} \tag{8}$$

with $r_\chi = \frac{m_{B_s}^2}{m_b(\mu) + m_s(\mu)}$. The Wilson coefficient F_V does not contribute in the lepton flavor conserving decays $B_s \rightarrow \mu^- \mu^+$ and $B_s \rightarrow \tau^- \tau^+$. Within the SM, $F_A = C_{10}$ only contributes to $B_s \rightarrow \mu^- \mu^+$ and $B_s \rightarrow \tau^- \tau^+$. The lepton flavor violating decay $B_s \rightarrow \tau \mu$ is not allowed in the SM. Thus, the Wilson coefficients C_9 and C_{10} do not contribute to this decay. Next, we look at two models of NP that contribute to $B_{s,d} \rightarrow l_i^- l_j^+$ decays.

III. FLAVOR VIOLATING HIGGS DECAYS

In this section we consider the model where a neutral scalar boson X with mass ~ 125 GeV and flavor-violating couplings [15, 16] mediates the $B_{s,d} \rightarrow l_i^- l_j^+$ decays. In this model, the effective Lagrangian which describes the possible flavor-violating couplings of X to SM fermion pairs in the mass basis is, [15, 16] :

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij} (\bar{f}_L^i f_R^j) X + h.c + \dots, \tag{9}$$

where ellipses denote nonrenormalizable couplings involving more than one Higgs field operator. $f_L = q_L, l_L$ are $SU(2)_L$ doublets, $f_R = u_R d_R, \nu_R, l_R$ are the weak singlets. The indices run over generations and fermion flavors with summation implicitly understood. In the SM the Higgs couplings are diagonal, $Y_{ij} = (m_i/v)\delta_{ij}$ with $v = 246$ GeV, but in general NP models the structure of the Y_{ij} can be different. The couplings in Eq. (9) will also lead to the decay $b \rightarrow s l_i^- l_j^+$ at tree level, mediated by a virtual X . The lagrangian gives

$$\begin{aligned}
R_{S(P)} &= \frac{1}{N_F} \frac{Y_{sb}(Y_{\mu\tau} + Y_{\tau\mu}^*)}{4m_X^2}, \\
R'_{S(P)} &= \frac{1}{N_F} \frac{Y_{bs}^*(Y_{\mu\tau} - Y_{\tau\mu}^*)}{4m_X^2}, \\
R_{V(A)} &= R'_{V(A)} = 0.
\end{aligned} \tag{10}$$

The branching ratio for the $B_s \rightarrow \mu^- \tau^+$ decay can be obtained from Eq. (7) as,

$$\begin{aligned}
Br(B_s \rightarrow \mu^- \tau^+) &= \frac{\tau_{B_s}}{\hbar} \frac{f_{B_s}^2 m_{B_s}^5}{512\pi(m_b(\mu) + m_s(\mu))^2} \times \sqrt{\left[1 - \left(\frac{m_\tau + m_\mu}{m_{B_s}}\right)^2\right] \left[1 - \left(\frac{m_\tau - m_\mu}{m_{B_s}}\right)^2\right]} \\
&\times \frac{|Y_{sb} - Y_{bs}^*|^2}{m_X^4} \left\{ \left[1 - \left(\frac{m_\tau + m_\mu}{m_{B_s}}\right)^2\right] |Y_{\mu\tau} + Y_{\tau\mu}^*|^2 + \left[1 - \left(\frac{m_\tau - m_\mu}{m_{B_s}}\right)^2\right] |Y_{\mu\tau} - Y_{\tau\mu}^*|^2 \right\}. \tag{11}
\end{aligned}$$

Also, the branching ratio for the $B_s \rightarrow l^- l^+$ ($l = \mu, \tau$) decays is,

$$\begin{aligned}
Br(B_s \rightarrow l^- l^+) &= \frac{\tau_{B_s}}{\hbar} \frac{f_{B_s}^2 G_F^2 m_{B_s} \alpha_{em}^2 |V_{tb} V_{ts}^*|^2}{64\pi^3} \sqrt{1 - \frac{4m_l^2}{m_{B_s}^2}} \left[\left(1 - \frac{4m_l^2}{m_{B_s}^2}\right) \left| \frac{Re[Y_{ll}](Y_{sb} - Y_{bs}^*)}{2m_X^2 N_F (m_b(\mu) + m_s(\mu))} \right|^2 \right. \\
&\left. + \left(\frac{2m_l}{m_{B_s}}\right)^2 |C_{10}|^2 \right], \tag{12}
\end{aligned}$$

where we assume Y_{ll} is real and set it to its SM value $Y_{ll} = m_l/v$.

Flavor violating Higgs coupling in Eq. (9) can generate flavor changing neutral currents at tree level. The couplings Y_{sb} and Y_{bs} are constrained by the mass difference ΔM_s in the $B_s - \bar{B}_s$ mixing. The $\Delta B = 2$ weak

Hamiltonian for this process can be found in the Ref. [16]. The theoretical expression for ΔM_s is given in Ref.[21]. It is found that one can reproduce the measured value of $\Delta M_s = (17.719 \pm 0.043)ps^{-1}$ [22] if

$$|Y_{sb} - Y_{bs}^*| \sim 10^{-3}. \quad (13)$$

The leptonic couplings $Y_{\mu\tau}$ and $Y_{\tau\mu}$ are constrained by the decays $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow 3\mu$, and the magnetic (δa_μ) and electric dipole (d_μ) moments. The theoretical expressions for $\Gamma(\tau \rightarrow \mu\gamma)$, $\Gamma(\tau \rightarrow 3\mu)$, $\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}$, and d_μ are taken from [16]. The experimental bounds for these observables are taken from [23–25]:

$$\begin{aligned} Br(\tau \rightarrow \mu\gamma) &< 4.4 \times 10^{-8} \\ Br(\tau \rightarrow 3\mu) &< 2.1 \times 10^{-8} \\ \Delta a_\mu &= (2.87 \pm 0.63 \pm 0.49)10^{-9} \\ -10 \times 10^{-20} e cm &< d_\mu < 8 \times 10^{-20} e cm. \end{aligned} \quad (14)$$

It is found that one can satisfy the above four experimental bounds if $|Y_{\mu\tau}| < 0.064$, $|Y_{\tau\mu}| < 0.061$ for $m_X = 125$ GeV. The fit results allow us to estimate the decay rate $Br(B_s \rightarrow \mu\tau) = Br(B_s \rightarrow \mu^- \tau^+) + Br(B_s \rightarrow \tau^- \mu^+)$.

The variations of the decay rates $Br(B_s \rightarrow \mu\tau)$ with $|Y_{sb} - Y_{bs}^*|$ and $|Y_{\mu\tau} + Y_{\tau\mu}^*|$ are shown in Fig. 1. Our result predict $Br(B_s \rightarrow \mu\tau)$ can be as large as $\sim 6 \times 10^{-6}$ for $m_X = 125$ GeV and $f_{B_s} = 0.229 \pm 0.006$ [26]. In the calculation we have used the experimental constraint $|Y_{\mu\tau} + Y_{\tau\mu}^*| < 0.10$. In this model, we obtain the

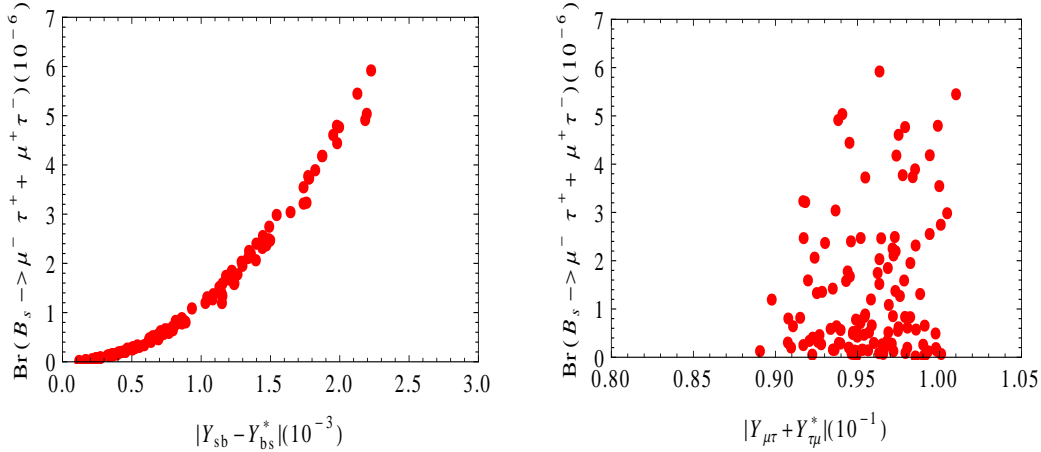


FIG. 1. The variation of $Br(B_s \rightarrow \mu^- \tau^+ + \mu^+ \tau^-)$ with the couplings $|Y_{sb} - Y_{bs}^*|$ and $|Y_{\mu\tau} + Y_{\tau\mu}^*|$ for $m_X = 125$ GeV and $f_{B_s} = .229 \pm 0.006$ GeV. Scatter points are allowed by ΔM_s^{exp} and experimental bounds in Eq. (14).

branching ratio $Br(B_s \rightarrow \mu^- \mu^+) < 4.3 \times 10^{-9}$ using $Y_{\mu\mu} = m_\mu/v$ with $v = 246$ GeV, $m_X = 125$ GeV and $f_{B_s} = 0.229 \pm 0.006$ GeV. The corresponding SM prediction is $\approx 3.17 \times 10^{-9}$. Our results for $Br(B_s \rightarrow \mu^- \mu^+)$ is consistent with the current upper limit $Br(B_s \rightarrow \mu^- \mu^+) = (3.2_{-1.2}^{+1.5}) \times 10^{-9}$ at 95% C.L. in Ref. [27]. Also, we obtain the branching ratio $Br(B_s \rightarrow \tau^- \tau^+) < 8.1 \times 10^{-7}$ using $Y_{\tau\tau} = m_\tau/v$ and $m_X = 125$ GeV. The values of this branching ratio in the SM is $\approx 6.81 \times 10^{-7}$. The latest LHCb-measurement of Γ_d/Γ_s implies a limit of $Br(B_s \rightarrow \tau^- \tau^+) < 3\%$ [28]. In passing we note that, the large width difference in the B_s meson system can changes these results by $\sim \mathcal{O}(10\%)$ as pointed out in [30–32].

Finally, in this model we obtain the tau longitudinal polarization fraction for the decays $B_s \rightarrow \mu^- \tau^+$:

$$\begin{aligned} P_L &= \frac{Br_{B_s \rightarrow \mu^- \tau^+}[\lambda_\tau = 1/2] - Br_{B_s \rightarrow \mu^- \tau^+}[\lambda_\tau = -1/2]}{Br_{B_s \rightarrow \mu^- \tau^+}[\lambda_\tau = 1/2] + Br_{B_s \rightarrow \mu^- \tau^+}[\lambda_\tau = -1/2]} = \sqrt{\left[1 - \left(\frac{m_\tau + m_\mu}{m_{B_s}}\right)^2\right] \left[1 - \left(\frac{m_\tau - m_\mu}{m_{B_s}}\right)^2\right]} \times \\ &\quad \left(2(|Y_{\mu\tau}|^2 - |Y_{\tau\mu}^*|^2)\right) / \left\{ \left[1 - \left(\frac{m_\tau + m_\mu}{m_{B_s}}\right)^2\right] |Y_{\mu\tau} + Y_{\tau\mu}^*|^2 + \left[1 - \left(\frac{m_\tau - m_\mu}{m_{B_s}}\right)^2\right] |Y_{\mu\tau} - Y_{\tau\mu}^*|^2 \right\}. \end{aligned} \quad (15)$$

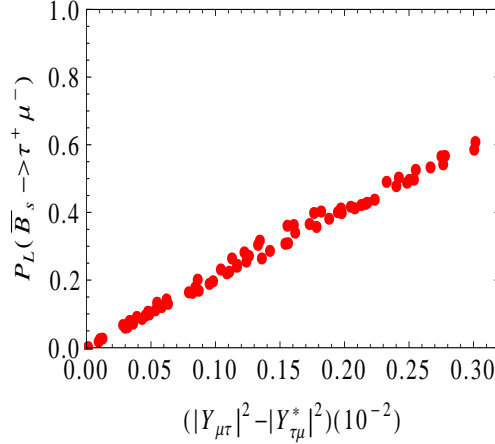


FIG. 2. Figure shows the $(|Y_{\mu\tau}|^2 - |Y_{\tau\mu}^*|^2)$ dependence of $P_L(B_s \rightarrow \mu^- \tau^+)$. Scatter points are allowed by ΔM_s^{exp} and experimental bounds in Eq. (14).

The result indicates P_L does not depend on the $b \rightarrow s$ couplings. Fig. 2 shows the dependency of P_L on the quantity $(|Y_{\mu\tau}|^2 - |Y_{\tau\mu}^*|^2)$.

The couplings Y_{db} and Y_{bd} for the decay $Br(B \rightarrow \mu\tau) = Br(B \rightarrow \mu^- \tau^+) + Br(B \rightarrow \tau^- \mu^+)$ are similarly constrained by the mass difference $\Delta M_d = (0.507 \pm 0.004)ps^{-1}$ [29]. The measured ΔM_d can be reproduced if $|Y_{db} - Y_{bd}^*| \sim 10^{-4}$. Using this result, we found the decay rate $Br(B \rightarrow \mu\tau) < 2 \times 10^{-7}$.

IV. SUPERSYMMETRY

The supersymmetry contributions to the process $B_s \rightarrow \mu^+ \tau^-$ are given by the one-loop box diagrams, shown in Fig 3, where charginos and neutralinos are exchanged. The interaction of charginos, neutralinos can be written as

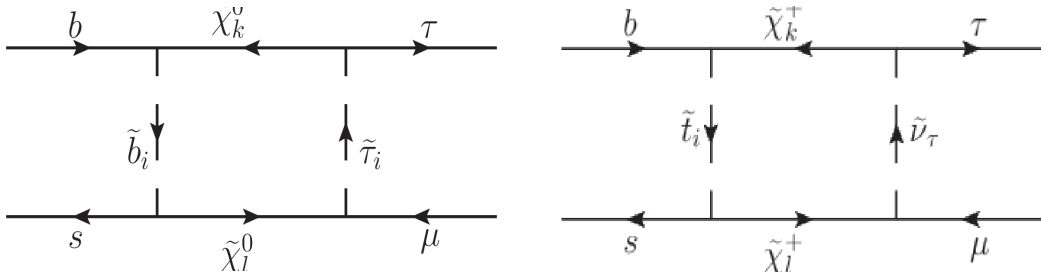


FIG. 3. One loop SUSY contributions to $B_s \rightarrow \tau^- \mu^+$.

$$\begin{aligned} \mathcal{L} = & \sum_{j=1}^2 \overline{\tilde{\chi}_j^-} \left[\tilde{u}_i^\dagger \left(G_{IJij}^{UL} P_L + G_{IJij}^{UR} P_R \right) d^I + \tilde{\nu}_j^\dagger \left(G_{IJj}^{LL} P_L + G_{IJj}^{LR} P_R \right) l^I \right] + hc \\ & + \sum_{k=1}^4 \overline{\tilde{\chi}_k^0} \left[\tilde{d}_i^\dagger \left(Z_{Iik}^{DL} P_L + Z_{Iik}^{DR} P_R \right) d^I + \tilde{l}_i^\dagger \left(Z_{Iik}^{LL} P_L + Z_{Iik}^{LR} P_R \right) l^I \right] + hc, \end{aligned} \quad (16)$$

where the mixing matrices in the super-CKM basis are given by [33]

$$G_{IJij}^{UL} = g \left[-V_{j1}^* (\Gamma^{UL})_{Ji} + V_{j2}^* (\Gamma^{UR})_{Ji} \frac{m_{u^J}}{\sqrt{2} M_W \sin \beta} \right] V_{JI}^{CKM}, \quad G_{IJij}^{UR} = g U_{j2} (\Gamma^{UL})_{Ji} \frac{m_{d^I}}{\sqrt{2} m_W \cos \beta} V_{JI}^{CKM}, \quad (17)$$

$$G_{IJj}^{LL} = -g V_{j1}^* (\Gamma^{\tilde{\nu}})_{IJ}, \quad G_{IJj}^{LR} = g U_{j2} (\Gamma^{\tilde{\nu}})_{IJ} \frac{m_l}{\sqrt{2} m_W \cos \beta}, \quad (18)$$

$$Z_{Iik}^{LL} = -\frac{g}{\sqrt{2}} \left[(N_{k2}^* + \tan \theta_W N_{k1}^*) (\Gamma^{LL})_{Ii} - N_{k3}^* (\Gamma^{LR})_{Ii} \frac{m_l}{m_W \cos \beta} \right], \quad (19)$$

$$Z_{Iik}^{LR} = -\frac{g}{\sqrt{2}} \left[2 \tan \theta_W N_{k1} (\Gamma^{LR})_{Ii} + N_{k3} (\Gamma^{LL})_{Ii} \frac{m_l}{m_W \cos \beta} \right], \quad (20)$$

$$Z_{Iik}^{DL} = -\frac{g}{\sqrt{2}} \left[(N_{k2}^* + \frac{1}{2} \tan \theta_W N_{k1}^*) (\Gamma^{DL})_{Ii} + N_{k3}^* (\Gamma^{DR})_{Ii} \frac{m_d}{M_W \cos \beta} \right], \quad (21)$$

$$Z_{Iik}^{DR} = -\frac{g}{\sqrt{2}} \left[\frac{2}{3} \tan \theta_W N_{k1} (\Gamma^{DR})_{Ii} + N_{k3} (\Gamma^{DL})_{Ii} \frac{m_d}{m_W \cos \beta} \right], \quad (22)$$

where $I, J = 1..3$ and $i = 1..6$. The matrices Γ 's are the matrices that diagonalize the squark and slepton mass matrices, while U and V are the unitary matrices that diagonalize the charged mass matrices. Finally, N is the matrix that diagonalizes the neutralino mass matrix.

One can easily show that the lightest stop gives the dominant effect for the chargino contribution. In this case, the amplitude is given by

$$A_{\tilde{\chi}^\pm} = \frac{G_F \alpha_{em} m_{B_s}^3 f_{B_s}}{2\pi} V_{ts}^* V_{tb} S(m_{\tilde{t}_i}, m_{\tilde{\nu}_j}, m_{\tilde{\chi}_k^+}, m_{\tilde{\chi}_l^+}) \left[\sqrt{1 - \frac{(m_\tau + m_\mu)^2}{m_{B_s}^2} \frac{F'_S - F_S}{m_b + m_s}} + \sqrt{1 - \frac{(m_\tau - m_\mu)^2}{m_{B_s}^2} \frac{F'_P - F_P}{m_b + m_s}} \right], \quad (23)$$

where

$$F_S = \frac{m_s (m_\mu V_{l1} U_{l2} + m_\tau U_{l2}^* V_{l1}^*) \Gamma_{33}^{\nu*} \Gamma_{23}^\nu}{\sin^2 \theta_W \cos^2 \beta} \left[\sqrt{2} V_{k1} U_{k2}^* ((\Gamma^{UL*})_{33})^2 + ((\Gamma^{UL*})_{36})^2 \right] - \frac{m_t}{m_W \sin \beta} V_{k2} U_{k2}^* ((\Gamma^{UL*})_{33} (\Gamma^{UR*})_{23} + (\Gamma^{UL*})_{36} (\Gamma^{UR*})_{26}), \quad (24)$$

$$F'_S = \frac{m_b (m_\mu V_{l1} U_{l2} + m_\tau U_{l2}^* V_{l1}^*) \Gamma_{33}^{\nu*} \Gamma_{23}^\nu}{\sin^2 \theta_W \cos^2 \beta} \left[(\sqrt{2} V_{k1} U_{k2} ((\Gamma^{UL*})_{33} (\Gamma^{UL})_{33} + (\Gamma^{UL*})_{36} (\Gamma^{UL})_{36}) \right. \\ \left. - \frac{m_t}{m_W \sin \beta} V_{k2} U_{k2} ((\Gamma^{UL})_{33} (\Gamma^{UR*})_{23} + (\Gamma^{UL})_{36} (\Gamma^{UR*})_{26}) \right], \quad (25)$$

$$F_P = \frac{\sqrt{2}}{m_W^2} \frac{m_s (m_\tau U_{l2}^* V_{l1}^* - m_\mu V_{l1} U_{l2}) \Gamma_{33}^{\nu*} \Gamma_{23}^\nu}{\sin^2 \theta_W \cos^2 \beta} \left[\left(\frac{m_t}{m_W \sin \beta} V_{k2} U_{k2}^* ((\Gamma^{UL*})_{33} (\Gamma^{UR*})_{23} + (\Gamma^{UL*})_{36} (\Gamma^{UR*})_{26}) \right. \right. \\ \left. \left. - \sqrt{2} V_{k1} U_{k2}^* U_{k2} ((\Gamma^{UL*})_{33})^2 + ((\Gamma^{UL*})_{36})^2 \right) \right], \quad (26)$$

$$F'_P = \frac{\sqrt{2}}{m_W^2} \frac{m_b (m_\tau U_{l2}^* V_{l1}^* - m_\mu V_{l1} U_{l2}) \Gamma_{33}^{\nu*} \Gamma_{23}^\nu}{\sin^2 \theta_W \cos^2 \beta} \left[\left(\frac{m_t}{m_W \sin \beta} V_{k2} U_{k2} ((\Gamma^{UL})_{33} (\Gamma^{UR*})_{23} + (\Gamma^{UL})_{36} (\Gamma^{UR*})_{26}) \right. \right. \\ \left. \left. - \sqrt{2} V_{k1} U_{k2} ((\Gamma^{UL})_{33} (\Gamma^{UL*})_{33} + (\Gamma^{UL})_{36} (\Gamma^{UL*})_{36}) \right) \right], \quad (27)$$

$$S(m_{\tilde{t}_i}, m_{\tilde{\nu}_j}, m_{\tilde{\chi}_k^+}, m_{\tilde{\chi}_l^+}) = \frac{m_{\tilde{t}_i}^2}{(m_{\tilde{t}_i}^2 - m_{\tilde{\nu}_j}^2)(m_{\tilde{t}_i}^2 - m_{\tilde{\chi}_k^+}^2)} \left[\left(\frac{m_{\tilde{t}_i}^2}{m_{\tilde{t}_i}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{t}_i}^2}{m_{\tilde{\chi}_l^+}^2} - \frac{m_{\tilde{\nu}_j}^2}{m_{\tilde{\nu}_j}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{\nu}_j}^2}{m_{\tilde{\chi}_l^+}^2} \right) \right. \\ \left. + \frac{1}{m_{\tilde{\nu}_j}^2 - m_{\tilde{\chi}_k^+}^2} \left(\frac{m_{\tilde{\nu}_j}^2}{m_{\tilde{\nu}_j}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{\nu}_j}^2}{m_{\tilde{\chi}_l^+}^2} - \frac{m_{\tilde{\chi}_k^+}^2}{m_{\tilde{\chi}_k^+}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{\chi}_k^+}^2}{m_{\tilde{\chi}_l^+}^2} \right) \right] \\ \left. + \frac{m_{\tilde{\chi}_k^+} m_{\tilde{\chi}_l^+}}{(m_{\tilde{t}_i}^2 - m_{\tilde{\nu}_j}^2)} \left[\frac{1}{(m_{\tilde{t}_i}^2 - m_{\tilde{\chi}_k^+}^2)} \left(\frac{m_{\tilde{t}_i}^2}{m_{\tilde{t}_i}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{t}_i}^2}{m_{\tilde{\chi}_l^+}^2} - \frac{m_{\tilde{\chi}_k^+}^2}{m_{\tilde{\chi}_k^+}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{\chi}_k^+}^2}{m_{\tilde{\chi}_l^+}^2} \right) \right. \right. \\ \left. \left. - \frac{1}{(m_{\tilde{\nu}_j}^2 - m_{\tilde{\chi}_k^+}^2)} \left(\frac{m_{\tilde{\nu}_j}^2}{m_{\tilde{\nu}_j}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{\nu}_j}^2}{m_{\tilde{\chi}_l^+}^2} - \frac{m_{\tilde{\chi}_k^+}^2}{m_{\tilde{\chi}_k^+}^2 - m_{\tilde{\chi}_l^+}^2} \ln \frac{m_{\tilde{\chi}_k^+}^2}{m_{\tilde{\chi}_l^+}^2} \right) \right] \right], \quad (28)$$

where $i, j, k, l = 1..2$ denote the heavy and light sparticles (stop-quark, sneutrino and chargino). In deriving these expression, the following hadronic matrix elements have been assumed:

$$\langle 0 | \bar{s} \gamma^5 b | \overline{B_s} \rangle = -i f_{B_s} \frac{m_{B_s}^2}{m_b + m_s}, \quad \langle 0 | \bar{s} b | \overline{B_s} \rangle = 0. \quad (29)$$

Similarly, the neutralino contributions can be written as

$$A_{\tilde{\chi}^0} = \frac{G_F \alpha_{em} m_{B_s}^3 f_{B_s}}{2\pi} S(m_{\tilde{b}_i}, m_{\tilde{\nu}_j}, m_{\tilde{\chi}_k^0}, m_{\tilde{\chi}_l^0}) \left[\sqrt{1 - \frac{(m_\tau + m_\mu)^2}{m_{B_s}^2}} \frac{R'_S - R_S}{m_b + m_s} + \sqrt{1 - \frac{(m_\tau - m_\mu)^2}{m_{B_s}^2}} \frac{R'_P - R_P}{m_b + m_s} \right]. \quad (30)$$

where

$$R_S = (Z_{23k}^{*D_R} Z_{33k}^{D_L} + Z_{26k}^{*D_R} Z_{36k}^{D_L})(Z_{33l}^{*L_R} Z_{23l}^{L_L} + Z_{33l}^{*L_L} Z_{23l}^{L_R}) \quad (31)$$

$$R'_S = (Z_{23k}^{*D_L} Z_{33k}^{D_R} + Z_{26k}^{*D_L} Z_{36k}^{D_R})(Z_{33l}^{*L_L} Z_{23l}^{L_R} + Z_{33l}^{*L_R} Z_{23l}^{L_L}) \quad (32)$$

$$R_P = (Z_{23k}^{*D_R} Z_{33k}^{D_L} + Z_{26k}^{*D_R} Z_{36k}^{D_L})(Z_{33l}^{*L_L} Z_{23l}^{L_R} - Z_{33l}^{*L_R} Z_{23l}^{L_L}) \quad (33)$$

$$R'_P = (Z_{23k}^{*D_L} Z_{33k}^{D_R} + Z_{26k}^{*D_L} Z_{36k}^{D_R})(Z_{33l}^{*L_L} Z_{23l}^{L_R} - Z_{33l}^{*L_R} Z_{23l}^{L_L}) \quad (34)$$

However, it turns out that the neutralino contribution is typically smaller than the chargino effect. Also in case of diagonal slepton mass matrix, which is severely constrained by the lepton flavor violation process such as $\mu \rightarrow e \gamma$ and $\tau \rightarrow \mu \gamma$, the neutralino contribution identically vanishes, it means that $R_S = R'_S = R_P = R'_P \simeq 0$. In this case, the branching ratio of $B_s \rightarrow \mu^+ \tau^-$ is given by

$$Br(B_s \rightarrow \mu^+ \tau^-) = \frac{\tau_{B_s}}{\hbar} \frac{G_F^2 \alpha_{em}^2 m_{B_s}^5 f_{B_s}^2 |V_{ts}^* V_{tb}|^2}{64\pi^3} \sqrt{(1 - (\frac{m_\mu - m_\tau}{m_{B_s}})^2)(1 - (\frac{m_\mu + m_\tau}{m_{B_s}})^2)} \left[\left(1 - \frac{(m_\tau + m_\mu)^2}{m_{B_s}^2}\right) \left| \frac{F'_S - F_S}{m_b + m_s} \right|^2 + \left(1 - \frac{(m_\tau - m_\mu)^2}{m_{B_s}^2}\right) \left| \frac{F'_P - F_P}{m_b + m_s} \right|^2 \right] S^2(m_{\tilde{t}_i}, m_{\tilde{\nu}_j}, m_{\tilde{\chi}_k^+}, m_{\tilde{\chi}_l^+}). \quad (35)$$

For lightest stop and lightest sneutrino masses of order 200 GeV and lightest chargino mass of order 120 GeV, one finds that

$$S(m_{\tilde{t}_i}, m_{\tilde{\nu}_j}, m_{\tilde{\chi}_k^+}, m_{\tilde{\chi}_l^+}) \simeq 1.23 \times 10^{-4}. \quad (36)$$

Also with the largest possible off-diagonal elements in the stop and sneutrino mass matrices, one may obtain:

$$F_S - F_{S'} \simeq 93.35, \quad F_P - F_{P'} \simeq -82.87. \quad (37)$$

Therefore, one concludes that the SUSY contribution to the process $B_s \rightarrow \mu^+ \tau^-$ is of order

$$Br(B_s \rightarrow \mu^+ \tau^-) \simeq 3.43 \times 10^{-11}, \quad (38)$$

which is about 5 order of magnitudes smaller than the tree level contribution of two-Higgs doublet model, discussed in the previous section.

V. SUMMARY

In this paper we analyzed the rare decay $B \rightarrow \tau \bar{\mu} + \mu \bar{\tau}$ in two possible extensions of the SM. In particular, we considered the tree level contribution in 2HDM, where the decay is mediated by a light scalar which is identified by the recently observed state at LHC. In the second example, the one loop contribution to this process in MSSM was computed. We found that in the former scenario the branching ratio $B_s \rightarrow \tau \bar{\mu} + \mu \bar{\tau}$ is of order 10^{-6} ($B_d \rightarrow \tau \bar{\mu} + \mu \bar{\tau} \sim 10^{-7}$), while in the later scenario $BR(B_s \rightarrow \mu^+ \tau^-) \sim 10^{-11}$. Therefore, one concludes that

probing this lepton flavor violating process at the LHCb would be a significant hint for a non-traditional new physics beyond the SM that has a tree level FCNC.

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